

**Method for negative feedback controlling electrical power  
and negative feedback controlled power supply**

5 The present invention is directed to a method for negative  
feedback controlling electrical power delivered to an  
electrical load, which method comprises generically, and as  
known to the skilled artisan, monitoring the electrical  
power delivered to the load, thereby generating a  
monitoring signal, forming in dependency of the monitoring  
signal and of a rated value signal a control deviation  
10 signal and adjusting - via a controller as e.g. a  
proportional or proportional-integral controller - the  
electrical power delivered and monitored in function of the  
control deviation signal.

15 The present invention thereby departs especially from such  
method and power supply for delivering high power of at  
least 100 VA to a load.

20 It is an object of the present invention to provide such a  
negative feedback control method and, accordingly, such a  
negative feedback controlled power supply for superior  
accuracy of controlled power delivered to the load, with  
respect to a rated power value to be delivered.

25 Under a first aspect the present invention departs from a  
method for negative feedback controlling electrical power  
delivered to an electrical load as mentioned above, whereat  
monitoring the electrical power delivered to the load  
results first in an analog monitoring signal, which is then  
analog to digital converted so as to result in a digital  
monitoring signal.

30 Under a second aspect the present invention departs from a  
method for negative feedback controlling electrical power

delivered to an electrical load as mentioned above, whereat  
adjusting the electrical power delivered to the load and  
monitored is performed as a function of the control  
deviation signal - again via a respective controller - by  
5 means of Pulse-Width Modulation (PWM).

In a method for negative feedback controlling electrical  
power, whereat the controlled value, namely the power  
delivered to the load, is digitalized as under the first  
aspect of the present invention, the overall accuracy of  
10 the negative feedback control significantly depends on the  
accuracy of the analog to digital conversion of the  
monitored signal. As is well known in the art of analog to  
digital conversion, noise of the analog input signal leads  
to the fact that the digital output signal jitters by at  
15 least one least significant bit (LSB). This problem is  
customarily resolved by oversampling, i.e. by establishing  
a sampling rate which is considerably higher than  
necessitated by the spectrum of the analog signal to be  
converted. In fact, by oversampling a multitude of digital  
20 samples are generated in a predetermined time frame, and  
the respective digitalized output value is formed by  
averaging the digital samples. Nevertheless, oversampling  
is always limited by the layout of a specifically  
considered converter not suited to handle sampling rates  
25 above a specific maximum rate. For rising the sampling rate  
over such limit makes it necessary to apply a differently  
designed A/D-converter which is often much more expensive  
and more critical to operate.

Under the generic object of the present invention as  
30 outlined above, and under the first aspect, it is therefore  
an object of the present invention to provide for an

increased conversion accuracy of A/D-conversion of the monitoring signal, thereby avoiding the above mentioned drawbacks.

5 This object is inventively resolved by the method mentioned above and according to the preamble of claim 1, at which the analog monitoring signal is analog to digital converted by performing the analog to digital conversion at least twice in parallel, according to the characterizing part of claim 1.

10 Thereby, at least two analog to digital converters, each construed for a predetermined sampling rate, are operated in parallel. This leads to an overall conversion with at least double that sampling rate, wherefore each of the converters is construed for, if both converters - as  
15 preferred - are operated at equal sampling rates.

Under the second aspect of the present invention the following has to be considered: Whenever a method for negative feedback controlling electrical power delivered to an electrical load comprises adjusting the electrical power  
20 delivered to the load and monitored by means of PWM, accuracy of adjustment is significantly limited by the predetermined minimum pulse-width adjustment increment by which pulse length may be at all adjusted.

It is therefore a further object of the present invention,  
25 at a method as mentioned above, whereat, within the negative feedback loop, adjusting of the electrical power delivered to the load and monitored in function of the control deviation signal is performed by pulse-width modulation with a predetermined pulse repetition period, to  
30 improve adjustment accuracy beyond the limit set by the predetermined minimum pulse-width adjustment increment.

This object is resolved inventively and according to the characterizing part of claim 2 by calculating from the control deviation signal a desired pulse-width adjustment increment. Such a desired pulse-width adjustment increment will normally not accord with an integer multiple of the predetermined minimum pulse-width adjustment increment of the PWM considered. Therefore, and according to this second aspect of the present invention, a pulse of predetermined, preferably fixed length is not applied in every pulse repetition period, but only so often in time that, averaged over time, the adjustment by the integer multiple on one hand and/or the pulse accords with a pulse-width modulation adjustment with said desired pulse-width adjustment increment.

Thereby, one can exactly deal with any desired adjustment according to any fractions of the predetermined minimum pulse-width adjustment increment.

If e.g. the minimum predetermined pulse-width adjustment increment is of 30 nsec. and an actual control deviation would necessitate a pulse-width adjustment by an increment only of 10 nsec., then the calculation will reveal in preferred mode that the pulse of predetermined length as in a most preferred embodiment a pulse which is the predetermined minimum pulse-width adjustment increment of 30 nsec. is to be applied in every third pulse repetition period. This leads, time-averaged as by filtering, to the same result as applying a 10 nsec. pulse in every period of PWM.

If e.g. the control deviation signal reveals a desired pulse-width adjustment increment of 40 nsec., then there will be applied in each pulse repetition of the PWM one

predetermined minimum pulse-width adjustment increment and, additionally, in every third period an additional predetermined minimum pulse-width adjustment increment, if, as in the most preferred mode, the pulse is selected to be  
5 just this increment.

In other words, this inventive technique combines customary pulse-width adjustment technique of PWM with a pulse frequency modulation (PFM) technique, at which pulses of a predetermined fixed length, namely as preferred according  
10 to the predetermined minimum pulse-width, are applied at a varying frequency.

According to the wording of claim 3, in a most preferred embodiment of the inventive method and power supply both aspects of the invention as outlined above, namely of  
15 inventive A/D-conversion and of inventive adjustment by PWM and superimposed PFM, are combined.

Although the present invention under all its aspects may be used or realized for lower power supply, in a far preferred mode of operation, it is realized for controlling the  
20 electrical power of at least 100 VA delivered to a load, according to the wording of claim 13. According to the wording of claim 14, monitoring the electrical power delivered to the load may be performed by monitoring the current or voltage delivered to the load.

25 In spite of the fact that the above mentioned A/D-conversion at least twice in parallel, might be applied in cases too, where both conversions are performed at minimum required sampling rates, according to the wording of claim 4, additionally to the inventively performed parallel  
30 conversion, each of the A/D-conversions is performed with oversampling.

In spite of the fact that A/D-conversion in parallel could be performed in some cases at mutually different sampling rates, e.g. at sampling rates of integer ratio, in a preferred embodiment and according to claim 5, A/D-  
5 conversions are performed in parallel at respective equal sampling rate.

Such an equal sampling rate may vary in time, in some applications, e.g. where the bandwidth development of an analog signal to be monitored is known in advance.

10 Nevertheless, in a preferred embodiment according to claim 6, parallel A/D-conversions are performed at respective equal and constant sampling rates. In a further preferred mode the converters are operated synchronously, according to the wording of claim 7.

15 In a further preferred embodiment according to the wording of claim 8, each of the at least two parallel A/D-conversions is performed with a sampling rate of at least 100 kHz, thereby resulting in an overall sampling rate of two parallel conversions of 200 kHz.

20 Turning back to the present invention under its second aspect or under preferred combination of both of its aspects, in a preferred embodiment according to claim 9 in a most preferred embodiment the pulse of predetermined length - applied by PFM - is selected to be the incremental  
25 pulse of the predetermined minimum pulse-width adjustment increment. Although this pulse needs not necessarily be of constant length, this is clearly the preferred mode, according to claim 10.

Either - once again - the instantaneous control deviation  
30 may be corrected by an adjustment of the PWM pulse-width by an integer multiple of predetermined minimum pulse-width

adjustment increments, or the instantaneous control deviation may only be accurately corrected by adjusting pulse-width modulation as was just explained and by additionally providing for applying pulses, preferably of the predetermined minimum pulse-width adjustment increments, by pulse frequency modulation, i.e. with a variable repetition rate, namely so often in time as necessary to deal with a control deviation which necessitates applying a PWM-adjustment by a fraction of the predetermined minimum pulse-width adjustment increment.

Nevertheless, the case may also occur, where no pulse-width modulation adjustment at all is necessary, in these cases, namely for down to zero adjustments only, the single pulses, preferably of an extent according to the predetermined minimum pulse-width adjustment increment, are applied with the (modulatable) repetition rate set as necessary.

Thereby and in a further preferred mode, at the pulse frequency modulation, the accordingly modulated pulse repetition period is modulated by an integer multiple of the pulse repetition period of the pulse-width modulation, according to claim 11.

For resolving the above mentioned object under the first aspect of the present invention there is further proposed a negative feedback control power supply according to the wording of claim 15. Under its second aspect a negative feedback control power supply according to the wording of claim 16 resolves the above mentioned object, and in a far preferred mode the objects under both of the aspects of the present invention are resolved by the digital negative



feedback control power supply according to claim 14, which combines both aspects of the present invention.

Preferred embodiments of the inventive negative feedback control power supply under both its aspects are further defined in the claims 18 and 19 and will additionally become apparent from the following detailed description. Further, the inventive power supply, especially combining both aspects, is applied to magnet-supply of a synchrotron, thereby resulting in an inventive synchrotron system as of claim 20. In the detailed description, preferred embodiments of the present invention will be described as examples and referring to figures. These figures show:

Fig. 1 By means of a simplified functional block / signal flow diagram an inventive negative feedback controlled power supply under the first aspect and operating according to the inventive method under its first aspect;

Fig. 2 qualitatively, control input trains applied to a parallel operated analog to digital converter as provided in the embodiment of fig. 1;

Fig. 3 in a simplified functional block / signal flow representation according to the representation of fig. 1, a further preferred embodiment of the present invention under its second aspect, namely of a further embodiment of an inventive power supply operating according to an inventive method;

Fig. 4 in a simplified functional block / signal flow diagram, a possible structure of a calculation unit as incorporated in a controller unit as of the embodiment of fig. 3;



Fig. 5 a time diagram of superimposed pulse-width modulation and pulse-frequency modulation as realized by the embodiment according to the figs. 3 and 4;

5 Fig. 6 a preferred form of superimposed pulse-width modulation and pulse frequency modulation as preferably realized in the embodiment according to figs. 3 and 4, and

10 Fig. 7 in a representation according to fig. 4, a today's most preferred embodiment.

15 In fig. 1 there is shown, by means of a simplified functional block / signal-flow diagram a preferred embodiment of the negative feedback controlled power supply according to the present invention and operating according to a preferred variant of the inventive method, both under the first aspect of the present invention.

20 According to fig. 1 uncontrolled electrical power line  $P_e$  is fed to a power input  $E_1$  of a power adjusting unit 1. From a power output  $A_1$  of unit 1 the adjusted or controlled power line  $P_a$  is led to an electrical load 3. A monitoring input  $E_5$  of a monitoring unit 5 is operationally connected to power line  $P_a$ , thereby monitoring load current and/or load voltage. Generically the adjusted power on line  $P_a$  at the output  $A_1$  of adjusting unit 1 is monitored by

25 monitoring unit 5 as the measured controlled value  $X_m$  of the negative feedback control loop to be further described.

The output signal  $X$  and respectively the output  $A_5$  of monitoring unit 5 are operationally connected to a difference-forming unit 7, whereat the signal from  $A_5$  is

30 subtracted from a rated value signal  $W$ , which is selected

at a rated value generating source 9. In spite of the fact that this rated value source 9 is shown in fig. 1 incorporated within controller unit 7, a rated value signal W may clearly be fed to that control unit 7 from an external signal source.

At the output  $A_{11}$  of difference forming unit 11, whereat, from the said rated value signal W and from the controlled value signal X a control deviation signal  $\Delta$  is formed, which is fed to a controller 13, the output thereof being operationally connected to a control output  $A_7$  of controller unit 7. Output  $A_7$  is operationally connected to control input  $C_1$  of adjusting unit 1.

According to the embodiment of fig. 1 and thereby according to the present invention under its first aspect, the input  $E_5$  of the monitoring unit 5 with the analog monitoring signal  $X_m$  is operationally connected to the analog inputs  $E_{15a}$  and  $E_{15b}$  of at least two analog to digital converters (ADC) 15a and 15b of monitoring unit 5. The digital signal outputs  $A_{15a}$  and  $A_{15b}$  of the ADCs 15a, 15b are operationally connected to superimposing unit 17.

The monitoring unit 5 further comprises a sampling/converting control unit 19 generating at two outputs  $A_{19a}$ ,  $A_{19b}$  respective pulse trains which are fed to sample/conversion control inputs  $C_{15a}$  and  $C_{15b}$  at the respective ADCs 15a and 15b.

As shown in fig. 2 the sampling/converting control signals  $Sc_{15a}$  and  $Sc_{15b}$ , and especially their edges as of e are preferably in synchronism, so that the two ADCs 15a and 15b, which are operated in parallel, perform sampling simultaneously.

Nevertheless, it is also possible to operate the converters

- staggered in time and/or
- at time varying sampling rates and/or
- at different sampling rates

5 in some cases.

Thereby, the sampling rates at the at least two ADCs are most preferably selected to perform oversampling.

At the output of superimposing unit A<sub>17</sub> the conversion results of the at least two ADCs 15a, 15b appear as  
10 respective digital words.

The output A<sub>17</sub> and thus the conversion result signals are fed to an averaging unit 21, which performs digital averaging of the digital signals provided from A<sub>17</sub>. If  
15 sampling and especially oversampling each of the converters 15 provides for n digital values, due to the fact that parallel conversion is performed,  $2 \cdot n$  or more generically  $k \cdot n$  digital values are averaged.

Thus, the overall sampling rate is risen by the number k of parallelly processed conversions, without the need of  
20 resolving at a single ADC the problems for accordingly rising the oversampling rate.

Again in a simplified functional block / signal flow diagram, fig. 3 shows a negative feedback controlled power supply according to the present invention under a second  
25 aspect and operating accordingly to the second aspect of the method according to the present invention.

Electric power line P<sub>e</sub> is fed to the power input E<sub>30</sub> for uncontrolled power of a power adjusting unit 30. The output A<sub>30</sub> thereof for controlled power is operationally connected

to a power monitoring unit 35 and to an electrical load 3. Power monitoring unit 35 monitors load current and/or load voltage. Monitoring unit 35 needs not be construed as was explained in context with fig. 1. In most generic terms, monitoring unit 35 does not even provide for analog to digital conversion.

The output  $A_{35}$  of the monitoring unit 35 is operationally connected to input  $E_{37}$  of the controller unit 37. A control output  $A_{37}$  of unit 37 is operationally connected to control input  $C_{30}$  of adjusting unit 30.

The adjusting unit 30 is construed as a power pulse-width modulation unit. A control signal applied to control input  $C_{30}$  controls pulse-width within the pulse repetition period  $T_p$  of the pulse-width modulation PWM. Additionally, every pulse applied to  $C_{30}$  leads to transmission of power from  $E_{30}$  to  $A_{30}$  during the time extent of such pulse. Pulse-width modulation of power delivered to load 3 from power adjusting unit 30 may be said to be controlled by a control signal  $C_{PWM}$  defining for a controlling pulse-width modulated signal, which is generated within controller unit 37 by a pulse-width control unit 39. In block 39 the control signal  $C_{PWM}$  is shown as a pulse-width modulated analog signal, also it will be represented in preferred mode by a digital control signal.

Due to the specific layout of PWM power adjusting unit 30 and/or possibly pulse-width controlling unit 39, pulse-width  $T_{mod}$  of the pulse-width modulated power signal may only be changed by an integer number  $m$  of predetermined minimum pulse-width adjustment increment  $\delta_{min}$ . This

predetermined pulse-width minimum adjustment increment  $\delta_{min}$

limits adjusting accuracy of the power output to the electric load 3 and monitored by monitoring unit 35.

Still according to the invention under this second aspect, the output signal of monitoring unit 35 is operationally

5 connected via input  $E_{37}$  of controller unit 37 to a difference forming unit 41, as controlled signal X. At difference forming unit 41 from the controlled value X and a rated value W generated by a rated value source 43 a control deviation signal  $\Delta$  is generated. The control  
10 deviation  $\Delta$  is fed via a controller (not shown here) to a calculating unit 43.

Fig. 4 shows in more details, what operations are principally performed inventively at calculation unit 43.

In function of the actual control deviation signal  $\Delta$   
15 calculation unit 43 determines as schematically shown in fig. 4 in block 45 a desired adjustment  $\delta_{des}$  which would have to be applied to the control input  $C_{30}$  of power adjusting unit 30 to negative feedback control the power  $P_a$  delivered to the electric load 3 exactly to match the  
20 desired value W so that  $\Delta$  becomes at least approximately zero. Nevertheless, and as was explained, power adjusting unit 30 and/or pulse-width modulation control unit 39 are limited with respect to the minimum predetermined adjustment increment  $\delta_{min}$  with which pulse-width  $T_{mod}$  may be  
25 changed. Therefore, the present invention under this aspect considers that although no pulse-width adjustment increments may be applied which are smaller than  $\delta_{min}$ , frequency with which a pulse-width adjustment is applied is an additional parameter which allows controlling the effect  
30 on the power output at  $A_{30}$ .

As will be explained, the drawback that pulse-width modulation provides for a predetermined minimum pulse-width adjustment increment  $\delta_{min}$  is bypassed by introducing additionally to pulse-width modulation PWM, pulse frequency modulation PFM. We understand by pulse-frequency modulation PFM applying pulses of predetermined fixed length and varying the repetition rate of these pulses.

Following this principle, the calculation unit determines the repetition rate of pulse frequency modulation with pulses preferably with an extent of  $\delta_{min}$  so as to adjust the power at  $A_{30}$  by less than is possible by varying  $T_{mod}$  by a single increment  $\delta_{min}$ .

As schematically shown in fig. 4 by block 47, calculating unit 43 determines as a possible form of realization the ratio  $R$  of the desired adjustment increment  $\delta_{min}$  and the predetermined minimal adjustment increment  $\delta_{min}$ . Let's assume this ratio results in a number  $R = 2.6$ . Unless the desired adjustment  $\delta_{des}$  accords exactly with an integer multiple of the predetermined minimum pulse-width adjustment increment  $\delta_{min}$ ,  $R$  may be written as  $R = I \cdot 10^0 + F \cdot 10^{-1}$  as of 2.6 with  $I = 2 \cdot 10^0$  and  $F = 6 \cdot 10^{-1}$ . Thus, the result of ratio forming in unit 47 is split in an integer  $I$  and a fraction  $F$ . The integer number  $I$  controls directly adjustment of pulse-width  $T_{mod}$  of the pulse-width modulation by the according number of increments  $I \cdot \delta_{min}$  in each pulse repetition period  $T_p$ . This accords to customary pulse-width modulation control.

The fractional number  $F$ , in the above example of 0.6, is used to apply additionally to the pulse-width modulation a pulse train, which is pulse frequency modulated PFM and

with a preferably fixed pulse, preferably of time extent  $\delta_{\min}$ . Thus, such additional pulse is not anymore applied in succeeding pulse repetition periods  $T_p$ , but just as often as necessary to have, averaged over time, the same effect on the power at  $A_{30}$  as if in every pulse repetition period  $T_p$  the pulse length would be changed by  $F \cdot \delta_{\min}$ , which is not feasible. If we take  $T_p$  as time unit, the time period with which an impulse of extent  $\delta_{\min}$  is to be applied becomes  $T_{PFM} = 1/F$ , thus for our example  $T_{PFM} = 1,67$ . Thus, instead of applying a respective adjustment of pulse-width in every time frame according to every pulse repetition period  $T_p$ , the repetition period prevailing for applying a single additional pulse of extent  $\delta_{\min}$  is modulated to  $(1:F) \cdot T_p$ .

In fig. 5 this superposition of pulse-width modulation adjusting and of pulse frequency modulation adjusting is exemplified. In every pulse repetition period  $T_p$  pulse width adjustment is performed with an adjustment according to  $I \cdot \delta_{\min}$  according to the above example by  $2 \cdot \delta_{\min}$ .

Additionally, there is superimposed the pulse frequency modulated signal consisting of fixed-extent pulses as of  $\delta_{\min}$  applied with a rate according to a repetition period of  $T_{PFM} = (1:F)T_p$ . Thus, in Fig. 3 the control signal to  $C_{30}$  becomes  $C_{PWM} + C_{PFM}$ .

Although this procedure is absolutely possible, it is not optimum in view of the fact that pulse-width modulation is clocked at a predetermined fixed rate according to  $T_p$  and that procedure according to fig. 5 may lead to pulse-width modulated signals overlapping with the frequency-modulated



impulse train. This situation would necessitate additional efforts to compensate for such occurrences.

Therefore, in a preferred embodiment the frequency-modulated signals with pulses of the extent  $\delta_{\min}$  are applied during  $F \cdot N$  of succeeding pulse repetition periods  $T_p$  wherein  $N$  stands for a number of succeeding pulse-repetition periods of pulse-width modulation. According to the above mentioned example and taking  $N$  e.g. to be 10, this means that the single pulse of  $\delta_{\min}$  is applied to 6 pulse repetition periods  $T_p$  out of 10.

Thereby, in fact frequency modulation is performed in discrete steps of pulse repetition period  $T_{pFM}$  which step being  $T_p$ . This preferred realization form is shown in fig. 4 by dashed lines.

This latter approach is further exemplified in fig. 6, where according to the above example out of 10 pulse repetition periods  $T_p$  of the pulse-width modulation, in 6 an additional pulse of  $\delta_{\min}$  is applied. Averaged over time the output power  $P_a$  of power adjusting unit 30 is adjusted accurately according to the desired pulse-width adjustment increment  $\delta_{des}$  which accords to the instantaneous control deviation  $\Delta$ .

In fig. 7 a most preferred form of PMW and PFM realization is shown as incorporated preferably in calculation unit 43.

The instantaneous control deviation  $\Delta$  is fed via the controller again to a unit 45, where, according to the instantaneous control deviation  $\Delta$ , a desired pulse-width adjustment increment  $\delta_{des}$  is calculated.

From this desired pulse-width adjustment increment  $\delta_{des}$ , as was explained in context with fig. 4, unit 47 determines the ratio  $R$  of  $\delta_{des}$  and the predetermined minimum pulse-width adjustment increment  $\delta_{min}$ . From the resulting ratio  $R$  ( $\delta_{des}/\delta_{min}$ ) the integer part  $I$  is stored and controls the adjustment of pulse-width of the pulse-width modulation by  $I \cdot \delta_{des}$ . Thereby, the control deviation  $\Delta$  drops so that  $R$  becomes smaller than unity according to the fraction  $F$  of the previously calculated value. The fraction  $F$  of the ratio  $R$  at the output of unit 47 is integrated or summed over time in a summing unit 48, preferably for each subsequent period  $T_p$ . The output of summing unit 48 is added as schematically shown in fig. 7 by adding unit 49 to the integer output of unit 47. Thus, as soon as time integral or the sum of the remaining fraction  $F$  of ratio  $R$  at the output of unit 48 reaches unity, the value  $I$  is incremented by one, and, in a single pulse repetition period  $T_p$  of pulse-width modulation, the prevailing pulse is additionally adjusted by the one predetermined minimum pulse-width adjustment increment  $\delta_{min}$ .

By this adjustment in that period  $T_p$  considered, the prevailing value of the control deviation and of the ratio  $R$  again drop. By resetting unit 48 as schematically shown at  $R_s$  in fig. 7 as soon as its output signal reaches unity, in the subsequent periods  $T_p$  pulse-width is kept adjusted by  $I \cdot \delta_{min}$ .

As shown in dashed line in fig. 7, instead of checking whether the sum of the subsequent values  $F$  of the ratio  $R$  reaches a value for incrementing  $I$  by unity, it is

absolutely possible to integrate or sum, preferably after the controller, the control deviation  $\Delta$ .

In a preferred embodiment of the inventive power supply and of the inventive method, both aspects according to fig. 1 and directed to accurate analog to digital conversion of the monitored power and according to the figs. 3 to 6 with respect to inventively adjusting the power fed to the electric load 3 in a negative feedback power control loop are combined to result in digital negative feedback control of the power supplied to a load 3.

By realizing such combined technique with two 16 bit analog to digital converters 15 according to fig. 1, each operated at a sampling rate of 100 kHz and by realizing pulse-width modulation with superimposed pulse frequency modulation as was described especially with the help of fig. 4 and 6 there was achieved an accuracy of resolution of at least 10 ppm and even down to a resolution accuracy of 1 ppm. This for a power supply for at least 100 VA power used for power supplying the magnet arrangement of synchrotron magnets.